

THE DESIGN AND IMPLEMENTATION OF THE INTEGRATED TIMING SYSTEM TO BE USED IN THE NATIONAL IGNITION FACILITY

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Abstract

The National Ignition Facility, or NIF, currently under construction at the Lawrence Livermore National Laboratory, will contain the world's most powerful laser. By the year 2003 the NIF laser will be a research tool allowing scientists a glimpse into plasma interactions that are equivalent to those found in the center of the sun. Every eight hours the NIF will generate 1.8 MJ of 351-nm light carried by 192 pulsed laser beams and focus it onto a pea-sized target. This will result in a fusion reaction between two isotopes of hydrogen, creating for a few hundred picoseconds stellar conditions. Synchronizing the beams and diagnosing the fusion reaction requires generation and delivery of over 1,000 precisely timed triggers to a multitude of systems.

The NIF Integrated Timing System (ITS) was developed to provide reliable, accurately timed triggers that allow each client system to operate independently during periods of shot preparation and maintenance, yet be coordinated to a few tens of picoseconds during the experiment. The ITS applies technologies developed for fiber communications and Two-Way Time Transfer, and integrates them by way of a computer communications network to achieve distributed control, dynamically configurable coordination and independence among timing channels, and integrated self-diagnostics.

INTRODUCTION

In the National Ignition Facility (NIF)¹⁻² currently under construction at the Lawrence Livermore National Laboratory in Livermore, California, the Integrated Timing System (ITS) has the responsibility of providing triggers to laser and diagnostic sub-systems. These triggers must be delivered at precisely programmed times during the interval within one second of an experiment, or "shot."

The NIF (cut-away view in Figure 1) is a pulsed laser that generates and amplifies precisely shaped 20-ns-long pulses of 1053-nm light in each of 192 separate beam paths. Once the energy in each beam reaches about 100 kJ, the light is frequency-tripled to 351 nm using non-linear crystal frequency converters, then focused onto sub-millimeter-scale targets to create extreme high-temperature/high-density conditions. The resulting physical conditions, including fusion of deuterium-tritium nuclei, is uniquely rich in laboratory experimental physics opportunities.

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Creating the desired target conditions requires that the 192 beams are synchronous at the target within 30 ps. Since the 192 optical paths are largely passive over the 3.5- μ sec long path, the simultaneity of beam arrival times is primarily determined by the time at which they are initially generated. As the light pulse traverses the laser, however, it is switched, amplified, and diagnosed by devices that require triggers. The ITS is responsible for providing triggers to each of the beam generators and to these devices such that the inter-beam timing is managed to obtain simultaneous arrival (or controlled temporal offsets).

The NIF building is scheduled for completion in the middle of the year 2000 and installation of equipment supporting the scientific objectives of NIF will begin. Installation of the ITS will be phased to match that of the 192 beamlines, as assembly of the NIF is planned to be incremental, allowing partial operations prior to completion. However, because the ITS is part of the basic NIF infrastructure, the bulk of it will be installed during the first year.

REQUIREMENTS

The requirements that the ITS must satisfy originate with the NIF physics objectives, flow down through System and Subsystem Design Requirements, and are managed with Interface Control Documents. Once the trigger needs of all NIF subsystems were identified, a set of specifications defining the functions, performances, and environment of the ITS was generated. The following characteristics summarize relevant requirements as they relate to the Integrated Timing System.

FUNCTIONALITY

During a shot all NIF subsystems must operate in concert, leading to control of facility-wide trigger timing to within a few tens of picoseconds. However, during the periods between shots staff who are performing preparation and maintenance tasks will want independent control of triggers to their systems. Thus, the ITS must be implemented in such a way that individual users each see it as "their" timing system, responsive to their current needs while not impacting other users.

In order to assure a high experimental availability of the NIF, each system (such as the ITS) is required to meet a predicted RAM (Reliability, Availability, and Maintainability) budget. This budget is translated into hours/year of system non-availability due to unplanned maintenance. The ITS is required to be designed such that anticipated unplanned downtime is less than 32 hours per year.

A NIF goal is to operate for thirty years, not necessarily without upgrading as an experimental physics facility, but with minimum modifications to the infrastructure. Thus, a guideline to implementing the ITS was to apply technology and components that are likely to be available and maintainable for an extended period of time.

PERFORMANCE

There are a total of about 1,000 independent trigger channels required by NIF clients. (Some of these triggers are further split to drive multiple devices at a nominally common time.) A review of client needs led to the definition of three levels of timing precision, referred to as Extended Range Fast, Fast, and Precise. Precise triggers, the most demanding, are specified as having less than 20 ps rms jitter and less than 100 ps drift over all environmental conditions. The ITS provides timing during the interval within one second of a shot; timing outside that interval is provided over a communications network using scheduling software to control devices.

ENVIRONMENT

The environment in which the ITS must perform is quite benign: optical components stability drives the requirement for an extremely stable temperature and humidity. Room air temperature is expected to be stable to ± 0.3 C and humidity 45% to 55%. Even so, fiber-optic path lengths of up to 500 m and varying electronic rack loading must be considered when end-to-end performance of a few tens of picoseconds is required.

ITS IMPLEMENTATION

The functional, performance, reliability, and lifetime requirements (and the opportunity to start with a “clean slate”) led us to explore timing system architectures quite different from those previously used on pulsed-laser facilities. In previous cases a single optical or electrical event was distributed over a tree structure, regenerated, and redistributed (potentially several times), until it eventually triggered many delay generators that generated outputs after a programmed time. Some limitations to this approach are:

- There is a single event generator for the entire facility, satisfactory during a shot, but restricting to a universal rate or single-shot trigger during set-up and maintenance periods.
- Each active element adds jitter (generally as root-sum-square) to the timing event, leading to buildup of jitter as multiple devices are traversed.
- As reconfiguration of trigger generation and distribution evolves (common for an experimental facility), changes inevitably affect those trigger channels that there was no intention to change. Even slight cable impedance changes might affect signal risetimes such that changes of hundreds of picoseconds is common.

After studying timing distribution techniques used in other similar (and sometimes dissimilar) facilities, an architecture that addresses most of these concerns was developed. In the course of implementation, we also effectively addressed the reliability and lifetime requirements of the NIF.

ARCHITECTURE

The ITS trigger distribution system utilizes fiber-optic communications, networking, and two-way time-transfer technologies. The general architecture is shown in Figure 2. A Master Clock provides stable 10 MHz and 1 PPS signals to the Master Timing Transmitter, which converts the 10 MHz to a standard communications frequency (155.52 MHz, SONET OC-3) that synchronizes an optical serial data stream output into a single-mode optical fiber. This optical signal is passively split and “broadcast” over fibers to 14 geographical zones that encompass the NIF. Within each zone the optical signal is further split up to 32 ways, each feeding an optical communications receiver located in a multi-channel delay generator. The data stream carries “trigger opportunities” (both periodic and single-shot) that delay generators are programmed individually to recognize and act on.

In each delay generator a very low jitter Clock Recovery Unit following the optical receiver recovers the clock from the serial data stream. This greatly attenuates clock jitter originating in the Transmitter and that may have built up during the transmission process. The data are also recovered from the data stream and decoded, then compared against a pattern that has been programmed into the delay generator (each channel can have a different pattern). A “match” between the received and programmed data constitutes a valid trigger event for that channel.

Following a pattern match for a given timing channel, there is a programmed delay before the delay generator generates an output. Unlike conventional delay generators that must accept a "Start" input that is asynchronous with the unit's clock, we are able to specify the start event as being synchronous with a clock edge. This removes a major source of jitter and non-linearity error. Additionally, the recovered clock serves as the timing reference for the coarse, or counter, portion of the delay generator. Thus, all delay generators have a common clock, keeping all of NIF in sync. Following the programmed number of counter steps, the remainder of the delay is generated by an analog vernier circuit. Errors contributed by this circuit include non-linearity, drift, crosstalk, and jitter, but careful design has addressed each of these, resulting in excellent performance of the delay generator.

At this point trigger timing stability is primarily due to the propagation path of optical fiber, passive optical splitters, and an electronic delay generator. Recognizing that even in the highly controlled environment of the NIF the optical propagation path length is subject to variations (both environmental and man-made), an additional capability has been designed into the system, using Two-Way Time-Transfer techniques. At the point where the serial data streams enter each of the 14 zones, a small fraction of the optical signal is picked off and returned to the area of the Transmitter by way of a second fiber in the same cable as the transmitting fiber. A multiplexed Measurement System, located adjacent to the Transmitter, receives, decodes, and compares this signal to a reference signal from the Transmitter, measuring the difference. This is the round-trip transit time of the fiber path to each zone. To a first order, the total path length is equally attributed to transmitting and receiving fibers (more importantly, changes are very likely to track). Each transmission path length is determined and a correction can be algebraically added to the requested delay setting for every delay generator in a given zone. In this way path-length changes due both to environment, and probably more importantly, human activity such as replacement of broken cables, are compensated.

IMPLEMENTATION SPECIFICS

In order to derive optimal benefit from vendors with skills in specific areas, the design and acquisition of the ITS was divided into two parts: the "Facility Timing System" portion and the "Local Timing Distribution" portion. Aside from fiber optic and coaxial cables and passive optical splitters, the primary components of these two portions are (for the Facility) a Transmitter and Measurement System and (for the Local portion) a programmable Delay Generator. Compatible specifications were created for each of these two elements, publicly bid, and awarded: the Transmitter and Measurement System to Timing Solutions Corporation (Boulder, CO) and the Delay Generator to a joint venture between Berkeley Nucleonics Corporation (San Rafael, CA) and Highland Technology Corporation (San Francisco, CA).

The specifications were written with the objective of applying components and technologies that are expected to have a long commercial lifetime. Specifically:

- Signal distribution over fiber optics was chosen as fiber has demonstrated a long service life,
- SONET OC-3 was chosen as the serial data rate as it is likely that both telecommunications and ATM industries will support long-term component availability,
- The delay generator is a VME module, a widely supported standard.

The general role of the optical data stream is to deliver common-timed trigger opportunities to delay generators. The serial data stream is transmitted as contiguous data frames, each initiated by a 16-bit frame sync pattern. The data portion of the frame follows the frame sync pattern, and is followed by a CRC-16 data verification word. A frame rate of 24,000 frames per second was chosen as that supports both the highest currently planned rate (960 Hz) and an alternative rate of 1000 Hz. "Fill bits" complete

the portion of the frame between the CRC-16 word and the following frame sync pattern. In order to maximize the quality of the recovered clock, 1-bit/2-bit (Bi-Phase) encoding was implemented to create a transition-rich data stream. Thus, while the bit rate is 155.52 MHz, the data rate is only 77.76 MHz.

One of the most significant design decisions was to define the contents of the serial data stream. Some capabilities were clearly necessary, others were desirable, and still others were considered to be of potential, if not immediate, value. In general, we chose to implement an extensive set of data, more than that necessary for currently foreseen operating modes, but hoping to anticipate possible future ones. We chose 16 data bytes as the message length.

The data bytes are of two basic types, each having two distinct components:

EXTERNALLY CONTROLLED DATA ("KEYS")

Synchronous keys to create single-shot events (there are 46 bits that serve as synchronous keys).

Some are 1-bit keys that allow independent operation of groups of delay generators and the remainder are "encoded" keys, allowing many more possible combinations, but only one key per one-second period. Synchronous keys are transmitted for 24,000 frames (one second) and are combined with other data bits to determine when a delay generator channel is triggered. Currently 32 bits are used as independent keys and 14 bits as encoded keys, but the mix is arbitrary so long as the software controlling the Transmitter and the Delay Generators is in agreement.

Asynchronous keys (2 bits) that are controlled by hardware connections to the transmitter and provide response within a single frame time. These keys are used as a near-real-time means to allow a fast-response enable/inhibit of delay-generator triggers.

INTERNALLY CONTROLLED DATA (PERIODIC RATES AND TIME-OF-DAY)

Periodic epochs (one byte). Each bit in this byte conveys a periodic rate from 960 Hz to 1/5 Hz (5 second period). Epochs are used both to support periodic triggers required by some NIF systems and for maintenance.

Real-Time Clock (9 bytes) has a resolution of one frame and a range of 10^6 days (the Modified Julian Day calendar is used). This provides the potential for programming a delay generator channel to trigger at a specified date and time, and through partial decoding also allows a periodic trigger to be generated at one of the epoch rates, but at an arbitrary phase relative to the periodic epochs.

FACILITY TIMING SYSTEM

The Facility Timing System consists of the Transmitter and the Measurement System. Both are provided by Timing Solutions Corporation. They are implemented separately, but use a common modular hardware structure that is a proprietary derivative of the standard PC bus.

TRANSMITTER

The ITS Transmitter provides 16 identical 1,550-nm optical outputs, each at a nominal 1-mW level, into single-mode fibers. The baud rate is 155.52 MHz, bi-phase encoded, resulting in a data rate of 77.76 Mbit/sec. Internally controlled data are calculated each frame and synchronized by the 1 PPS input to provide an encoded real-time clock and periodic epochs. The real-time clock is initialized by and confirmed against a Network Time Server with a resolution of 1 second.

Externally controlled data are provided through a local Ethernet interface between the Transmitter and an ITS Front End Processor (FEP), which communicates with clients and Supervisory software over the NIF Integrated Computer Control System (ICCS). The FEP writes the synchronous keys into the Transmitter,

which take effect during the next 1-second epoch. The FEP also initializes and monitors the real-time clock and monitors internal Transmitter operation. The two asynchronous keys are controlled by electrical inputs and are responsive within the period of one frame, ~ 41 microseconds. This provides a rapid-response capability to inhibit delay-generator triggers (shot abort) when necessary.

As currently implemented there are over 16,000 possible encoded keys (more than the planned number of timing channels) and each timing channel can be programmed to recognize a key. Thus, a grouping of from a single channel to the entire NIF ensemble can be arbitrarily and dynamically configured as a group that will respond to a specific key. Further, up to 16,000 groups of arbitrarily arranged timing channels may exist at any given time (although since only one encoded key can be transmitted during each one-second epoch the practical number is much smaller). At any given moment a timing channel can respond to only one encoded key.

The 32 bits that serve as independent keys are also transmitted for one second, but any combination may be sent allowing simultaneous, independent use by up to 32 groups of clients. It is possible for a delay generator channel to be programmed to respond to any number of the 32 independent keys concurrently, triggering whenever any one of them is received. The same dynamic configuration capability as for the encoded keys is present, but only 32 keys may be defined.

MEASUREMENT SYSTEM

The Measurement System makes an extremely accurate measurement of the time difference between a timing reference signal (received directly from the Transmitter) and up to 15 data streams returned from each of the local zones. The Measurement System uses optical receivers, clock recovery units, and data decoders to define the event to be measured, then a hybrid time-interval counter/phase measurement circuit to perform the measurement. The 15 measurements are stored and provided to the ITS FEP upon request, and software within the FEP utilizes these measurements to calculate and implement a correction in each delay generator channel on a zone-by-zone basis.

LOCAL TIMING DISTRIBUTION

DELAY GENERATORS

The ITS delay generators are implemented as single-width VME modules and provide eight channels per module. A block diagram of the delay generator is shown in Figure 3. Aside from a local trigger input provided primarily for maintenance and off-line operations, the normal operating mode is to use the optical serial data stream as the timing input. The serial data stream is detected and the carrier clock is recovered by a communications receiver. The data are scanned, seeking the frame sync pattern, and once observed the next 18 bytes are grabbed and stored in memory. During the remainder of the frame, while the fill bits are being received, two processes take place within the delay generator. First, a calculation to determine if the data is valid based on the CRC-16 word is performed. Then, if the data are error-free, a bit-by-bit comparison is made between the stored data and two 128-bit tables that were loaded into the delay generator by way of its VME interface.

One of these tables is a binary **“Don’t Care”** mask. It specifies which of the bits are relevant and which should be ignored. The second table is the **“Compare”** file. In order for a trigger to be generated by a given channel, ALL of the following must be true:

- The clock recovery circuit is deemed to be “In Lock,”
- a valid data frame has been acquired,
- the CRC-16 word confirms no error in the data portion of the frame (this can be disabled under software control), and
- every bit that matters (i.e. Don’t Care mask bit is a 0) matches the corresponding bit in the Compare file.

If all of these conditions are satisfied, then upon detection of the next frame sync pattern the timing channel will be started and an output will be generated after the programmed delay. Each timing channel has its own Don’t Care and Compare files.

During currently envisioned NIF operations, the real-time clock bits in the data frame will not be utilized. Future operating modes may find these useful. Keys and epochs will be decoded for single-shot and repetitive operation respectively. The asynchronous keys will be decoded by those channels, which could cause damage if triggered when laser conditions are not proper.

STATUS

As of December, 1999, we have received and evaluated a prototype Transmitter and four Delay Generators. The first-article Measurement System is in test and is scheduled for acceptance testing January, 2000.

TRANSMITTER/DELAY GENERATORS

Testing has been conducted primarily using two delay generators driven by the Transmitter (or a surrogate) after a 50-50 fiber-optic splitter. The parameters evaluated and measured results are shown in Table I and appear to exceed the Precise performance requirements.

More extensive long-term and environmental measurements are still to be made, as well as channel crosstalk (qualitative tests indicate insignificant impact, but more detailed testing remains).

MEASUREMENT SYSTEM

Measurements of the Measurement System performance have been made by the vendor as part of the development process and the results are extremely encouraging. Measurement noise is somewhat under 1 ps (rms) and stability over several hours in an uncontrolled laboratory environment is under 4 ps (peak to peak).

One common concern of both the Delay Generator and Measurement System is the delay sensitivity to optical power level variations. Commercial optical receivers have variable performance in this respect, as it is normally not a relevant parameter so long as the recovered clock and data are equally affected. Both vendors have addressed this issue and have developed techniques to manage the sensitivity to an acceptable level over the ± 0.5 dB range that has been specified. Part of the solution lies in the ability of the Transmitter vendor to maintain tight control of the optical power level of its optical output. The power level at the input of a delay generator may be in the range of -20 to -28 dBm, allowing for differences in the distribution of the optical signal; but once configured, a high degree of stability is expected. Because of high isolation in the optical splitters, addition or removal of delay generators is not expected to affect the optical power to other units supplied by the splitter.

SYSTEM INTEGRATION ISSUES

The ITS trigger distribution system has very sophisticated capabilities. As a result system integration and software development effort has been and continues to be substantial. However, drivers for the Delay Generator are complete and those for the Transmitter and Measurement System are in process. Graphical User Interfaces (GUI's) are also in development (along with those for other NIF devices) to support operator interface; and the timing channels are being integrated into the NIF data-base management system to support an integrated shot configuration process.

Within each zone, diagnostic time-measurement instrumentation is permanently installed and through a multiplexed monitoring capability in the delay generator we are able to monitor the performance of each unit, real-time and *in situ*. This capability will be used to detect equipment failures and other problems between shots, with the intent of uncovering and remedying maintenance issues before they have an impact on either the NIF schedule or timing performance quality.

CONCLUSIONS

The Integrated Timing System will provide flexible triggers to well over 1,000 devices in the National Ignition Facility with a precision of a few tens of picoseconds. It applies modern technology and a new architecture to provide timing clients with independence during set-up and maintenance periods, a measure of self-diagnostics to find, isolate, and support repair whenever a failure does occur, and a high degree of flexibility. Installation and activation will begin in mid-2000, and will continue for approximately three years, while incremental installation intermixed with periods of operation will occur.

ACKNOWLEDGMENTS

The NIF Integrated Timing System architecture extends a concept developed by R. L. Kremens³ at the University of Rochester Laboratory for Laser Energetics. Collaborative discussions between LLNL and the Commissariat à l'Énergie Atomique (Bruyères-le Châtel, France) during the early stages of architecture development has led to similar system designs at the NIF and the Ligne Integration Laser (LIL) facility near Bordeaux, France.

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- [2] Current information about the NIF can be found on the World Wide Web at:
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- [3] R. L. Kremens et al, "The OMEGA laser electronic timing system," Rev. Sci. Instrument. January, 1997, 68 (1), 943.

NOTE: Mention of a company or product by name is not intended to be construed as an endorsement or approval by the Lawrence Livermore National Laboratory or the University of California.

PARAMETER	MEASURED PERFORMANCE
Jitter (RMS, measured over 60 seconds)	
Channel-to-channel, same module	4.8 ps
Between channels in different modules	5.1 ps
Stability (Averaged, reference module in fixed environment)	
Temperature	1 ps/C
Optical Power Level	20 ps/8 dB change
Drift (channel-to-channel, over a weekend, uncontrolled office environment)	<25 ps peak-to-peak

Table I – Transmitter/Delay Generator Performance

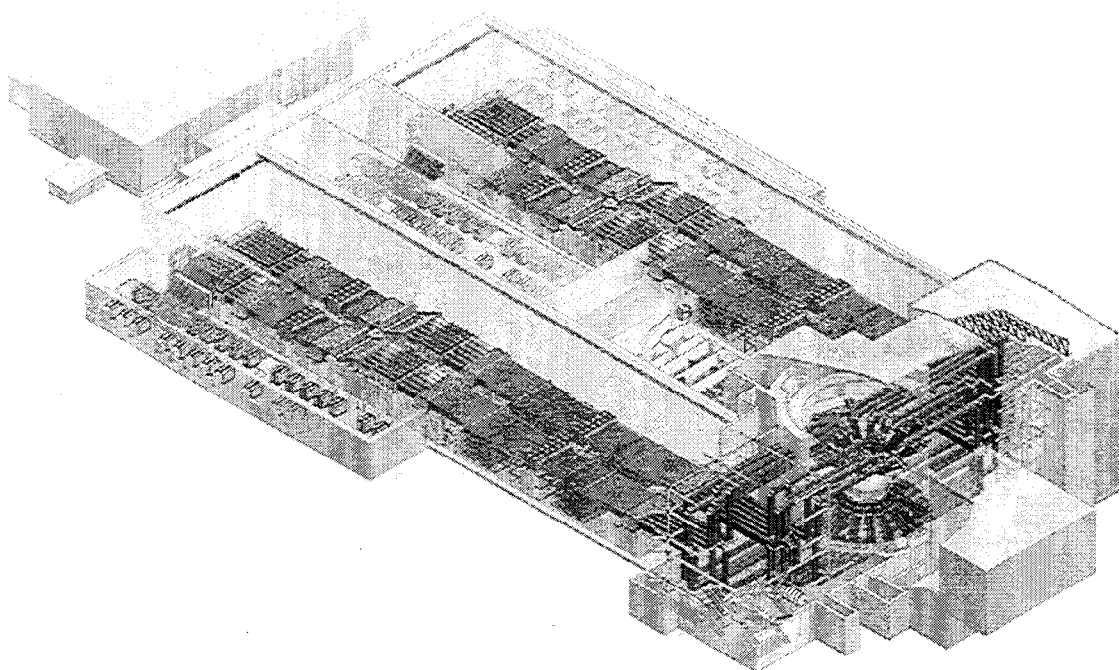


Figure 1 – National Ignition Facility (NIF) cut-away view.
The NIF building is 170 x 85 m and 30 m in height.

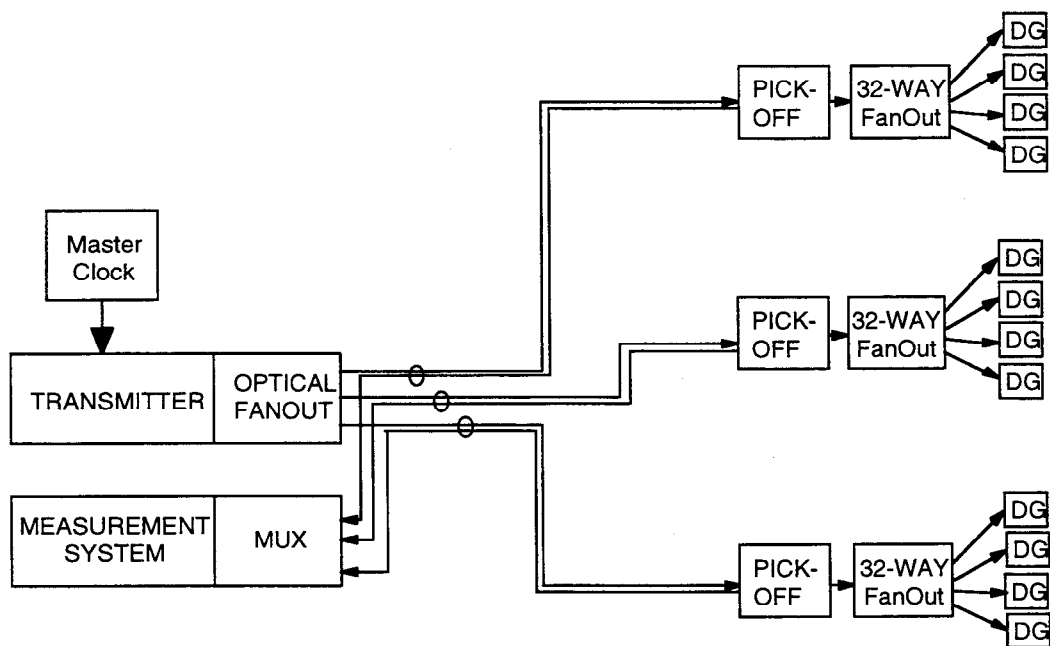


Figure 2 – Architecture of the Integrated Timing System Trigger Distribution

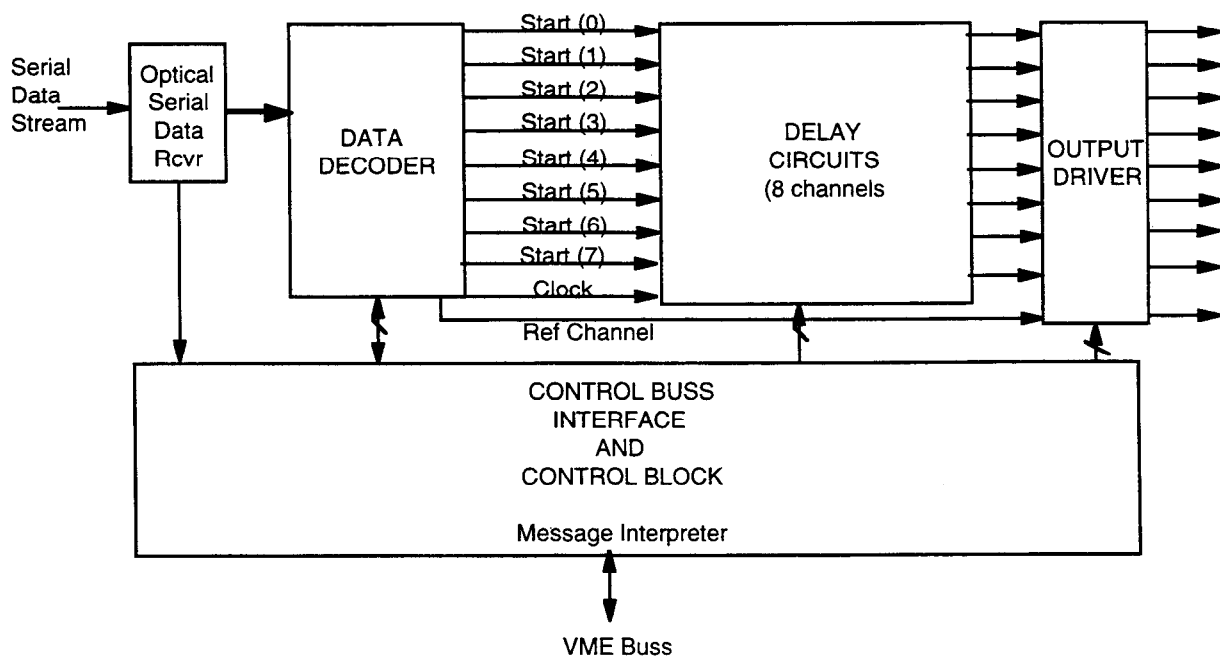


Figure 3 – Integrated Timing System Delay Generator Block Diagram